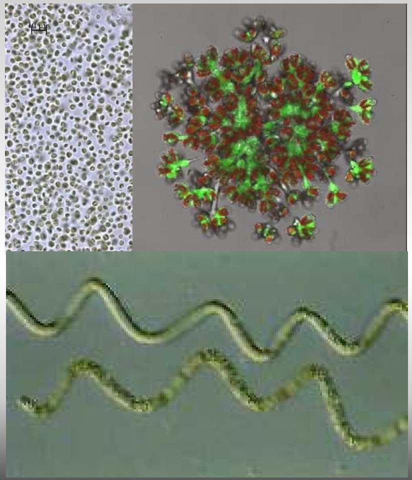
http://www.gepea.fr/

Benefits of MELiSSA loop project for microalgae industry, from the optimization of solar culture to the design of innovative intensified photobioreactor technologies



$$r_X = \rho\phi A - \mu s \frac{K_r}{K_r+G} X = \rho\phi A - \frac{J_{NADH_2} M_X}{\upsilon_{NADH_2-X}} \frac{K_r}{K_r+G} X$$

Jérémy Pruvost(1), Jean-François Cornet(2), Mariana Titica(1), Jack Legrand(1)
1 GEPEA, Université de Nantes, CNRS, UMR6144, bd de l'Université, CRTT - BP 406, 44602 Saint-Nazaire Cedex, France
2 Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, F-63000 Clermont-Ferrand, France

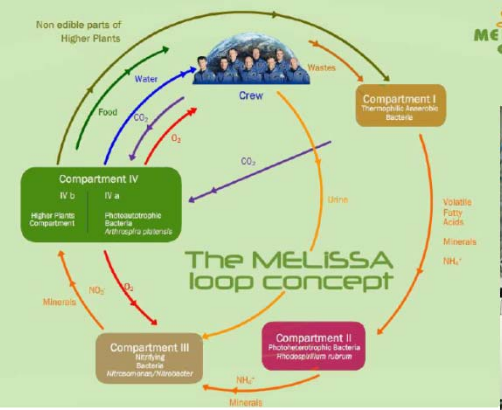
Outline of the lecture

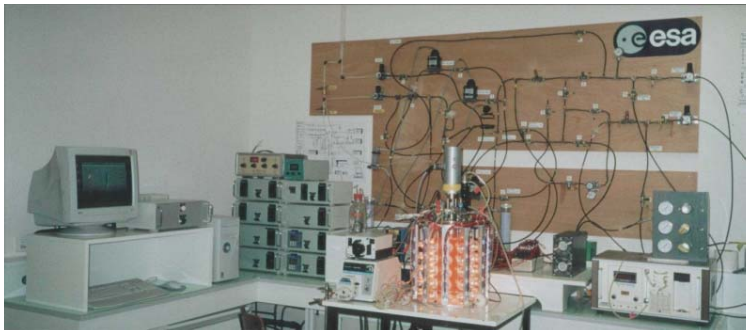
- Photobioreactor engineering: corpus of knowledge issued from MELISSA project
- Transposition to solar (terrestrial) culture
- A successful example: development of an intensified technology of solar PBR: AlgoFilm© technology

Photobioreactor engineering

MELiSSA corpus of knowledge

Institut Pascal research in Melissa Project

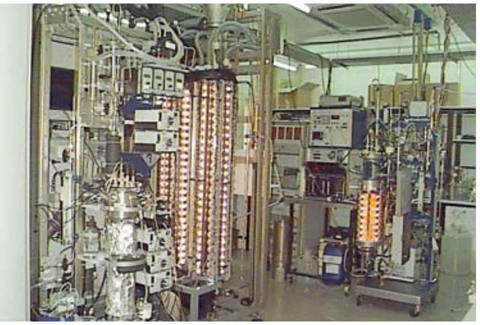




Courtesy from Institut Pascal (France)

Courtesy from Institut Pascal (France)

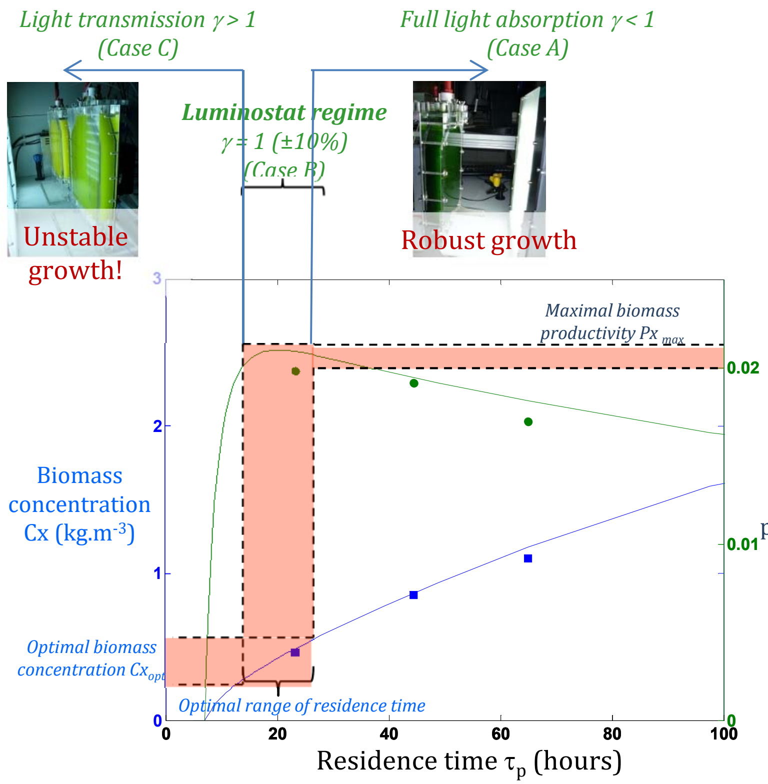
Courtesy from UAB (Spain)

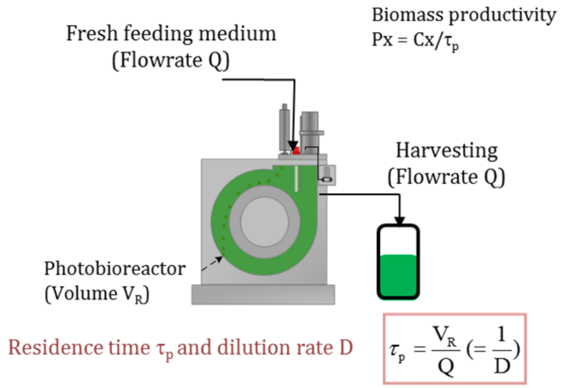


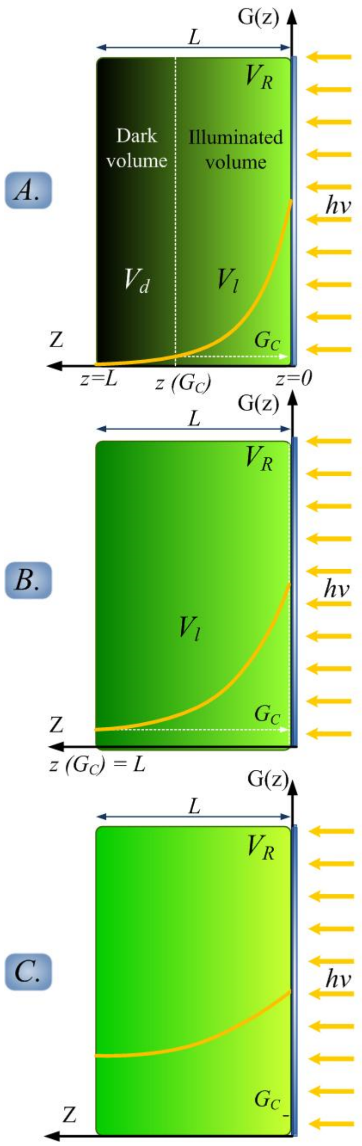
Courtesy from ESA / UAB

- Modeling artificially illuminated photobioreactors for the ESA-MELiSSA project with applications to simulation, design and model-based predictive control began in **1988** (first MELiSSA PhD Thesis of JF Cornet).
- During the last decades, and till now, this work was pursued at Institut Pascal (UCA) both on CII and CIVa compartments with numerous applications in the MOU MELiSSA (mainly in Spain with the MPP at UAB and in Belgium / Switzerland with experiments conceived and developed to flight onboard the ISS).
- A scientific collaboration between IP and GEPEA on the modeling of Solar PBR began in 2000 thanks to ESA…

The coupling between growth and light conditions



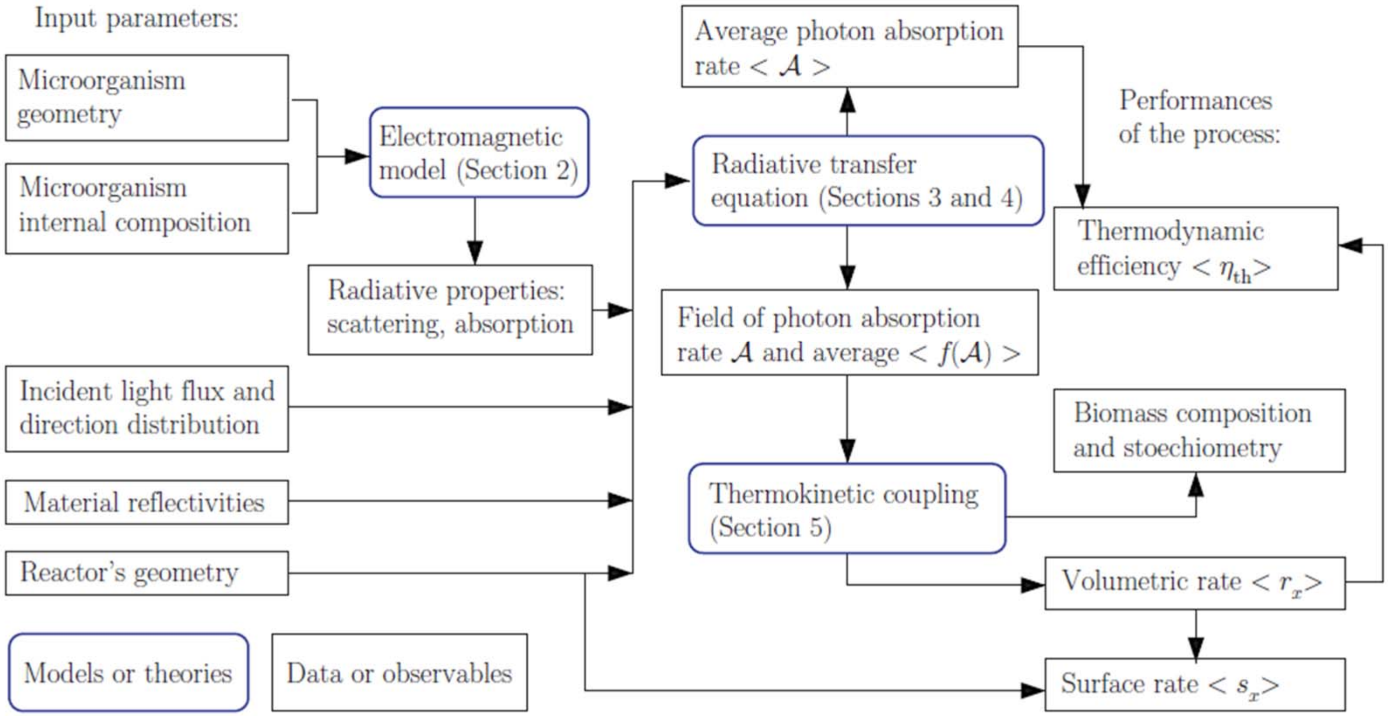




Cornet et al. (IP Institute) modeled the direct relation between light attenuation conditions and biomass productivity in PBR and then introduced the « γ=1 » concept to achieve maximal productivity through radiative transfer control

Cornet et al. 1994&95
Takache et al. 2012

MELISSA developments



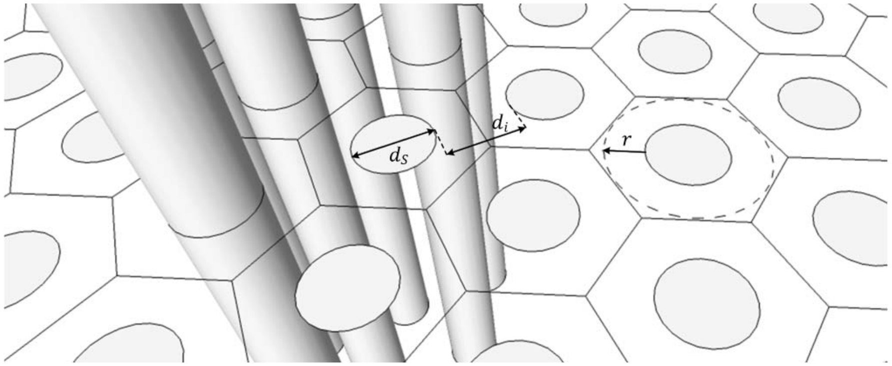
Dauchet et al. 2016

See Dauchet al., Photobioreactor Modeling and Radiative Transfer Analysis for Engineering Purposes, Advances in Chemical Engineering, Photobioreaction Engineering vol.48, 2016

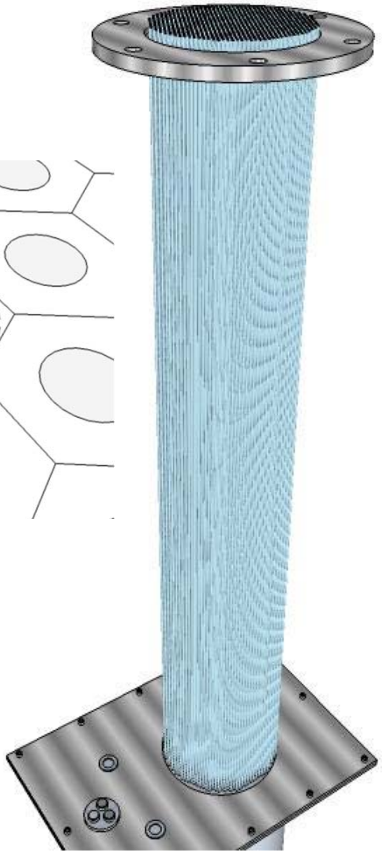
- After two decades of research, a robust and detailed knowledge modeling approach is now available.
- It combines advanced radiative transfer and kinetic growth models to predict photosynthetic growth in photobioreactors

Example#1 of application: optimal design of volumetrically illuminated PBR

See the poster « New generation photobioreactor characerization », Cornet et al.

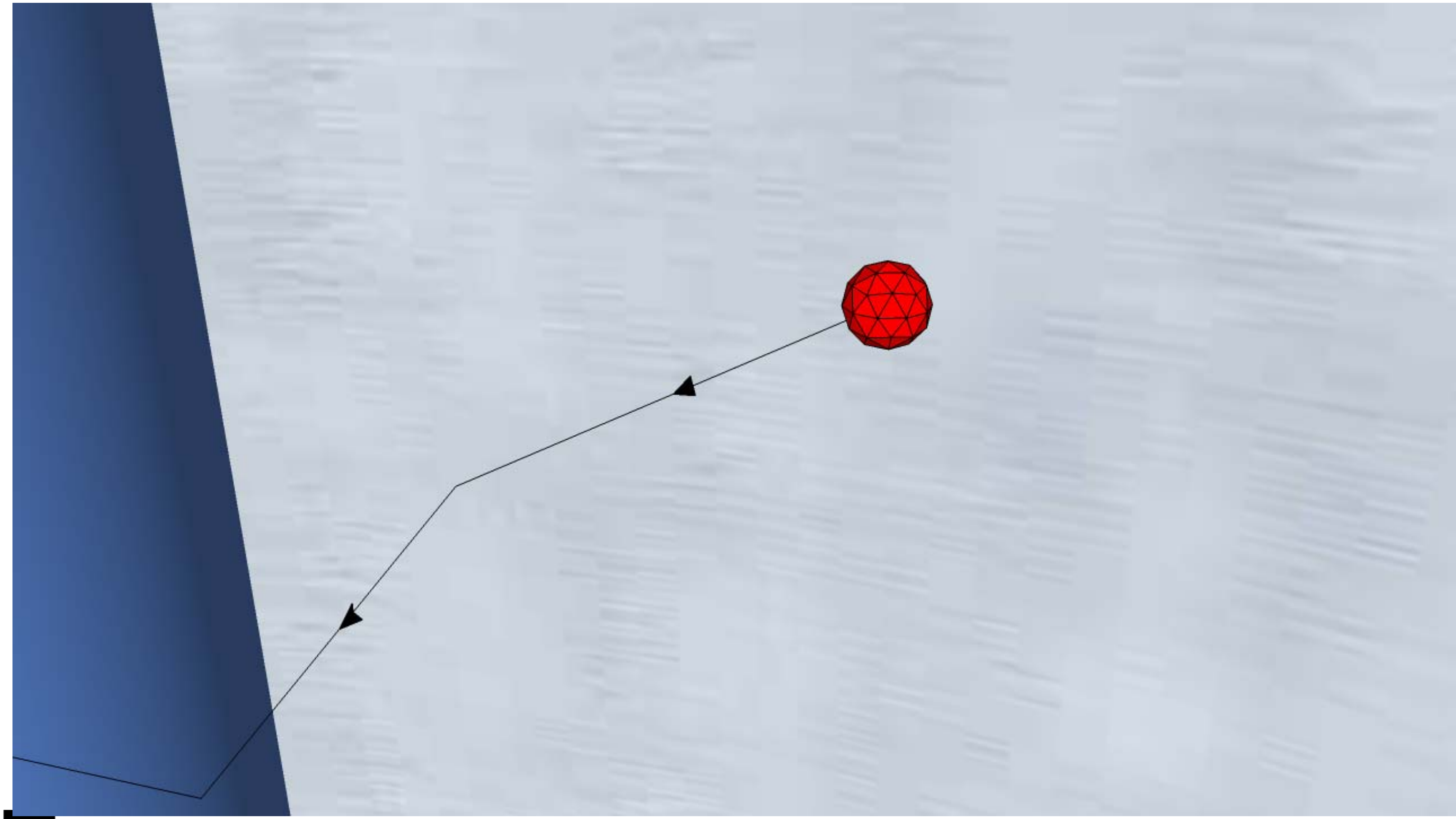


Courtesy from Institut Pascal (France)
(Rochatte, Dauchet and Cornet)



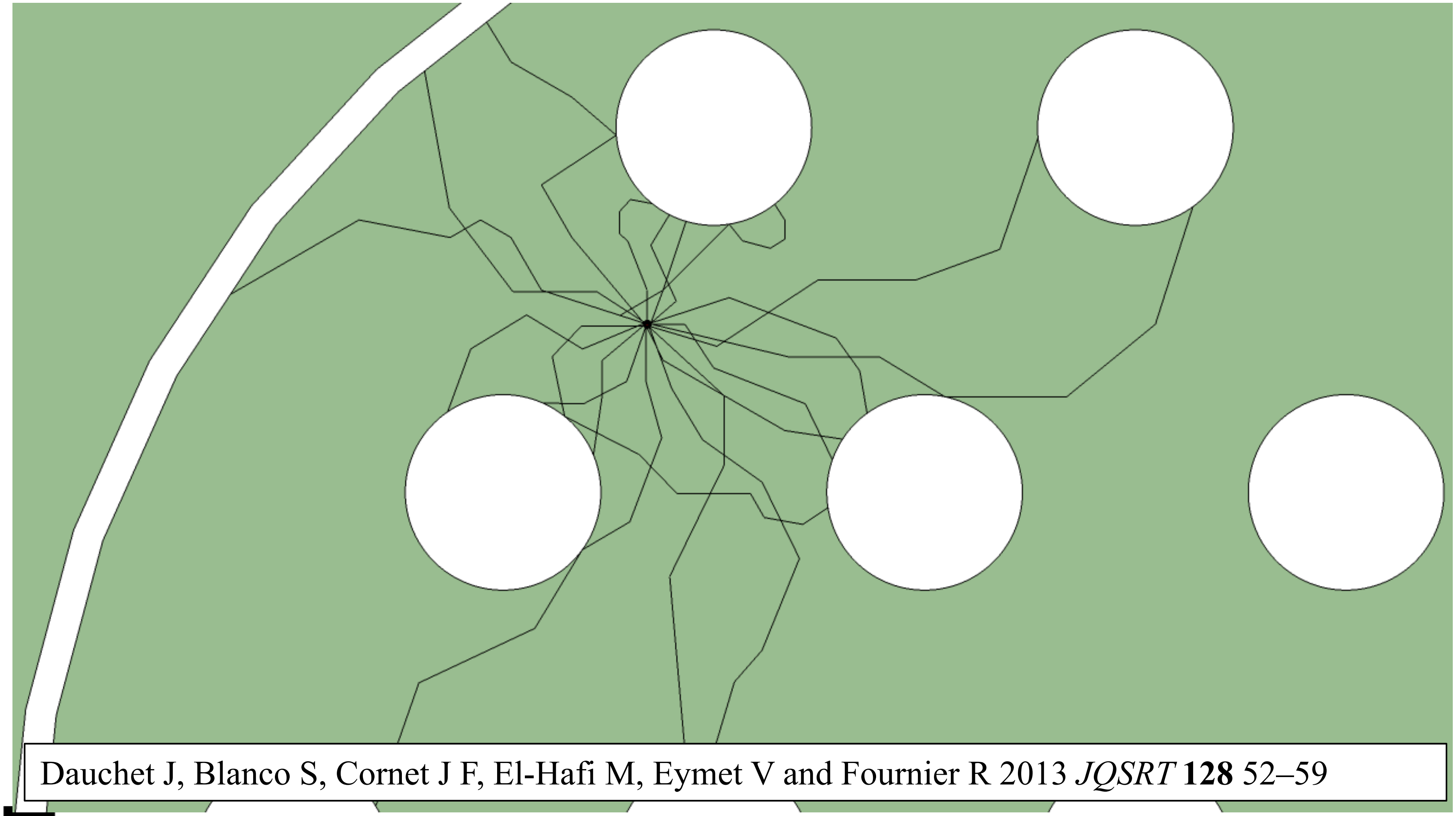
DiCoFluv PBR (captation/dilution of the flux in volume)

Example of result: optimal design of volumetrically illuminated PBR



Courtesy from Institut Pascal (France)
(Rochatte, Dauchet and Cornet)

Example of result: optimal design of volumetrically illuminated PBR



Dauchet J, Blanco S, Cornet J F, El-Hafi M, Eymet V and Fournier R 2013 *JQSRT* **128** 52–59

Example#2 of application : Predicting PBR performances

Examples of validation :

Dauchet et al, 2016

Adv. Chem. Eng.

chapter 1

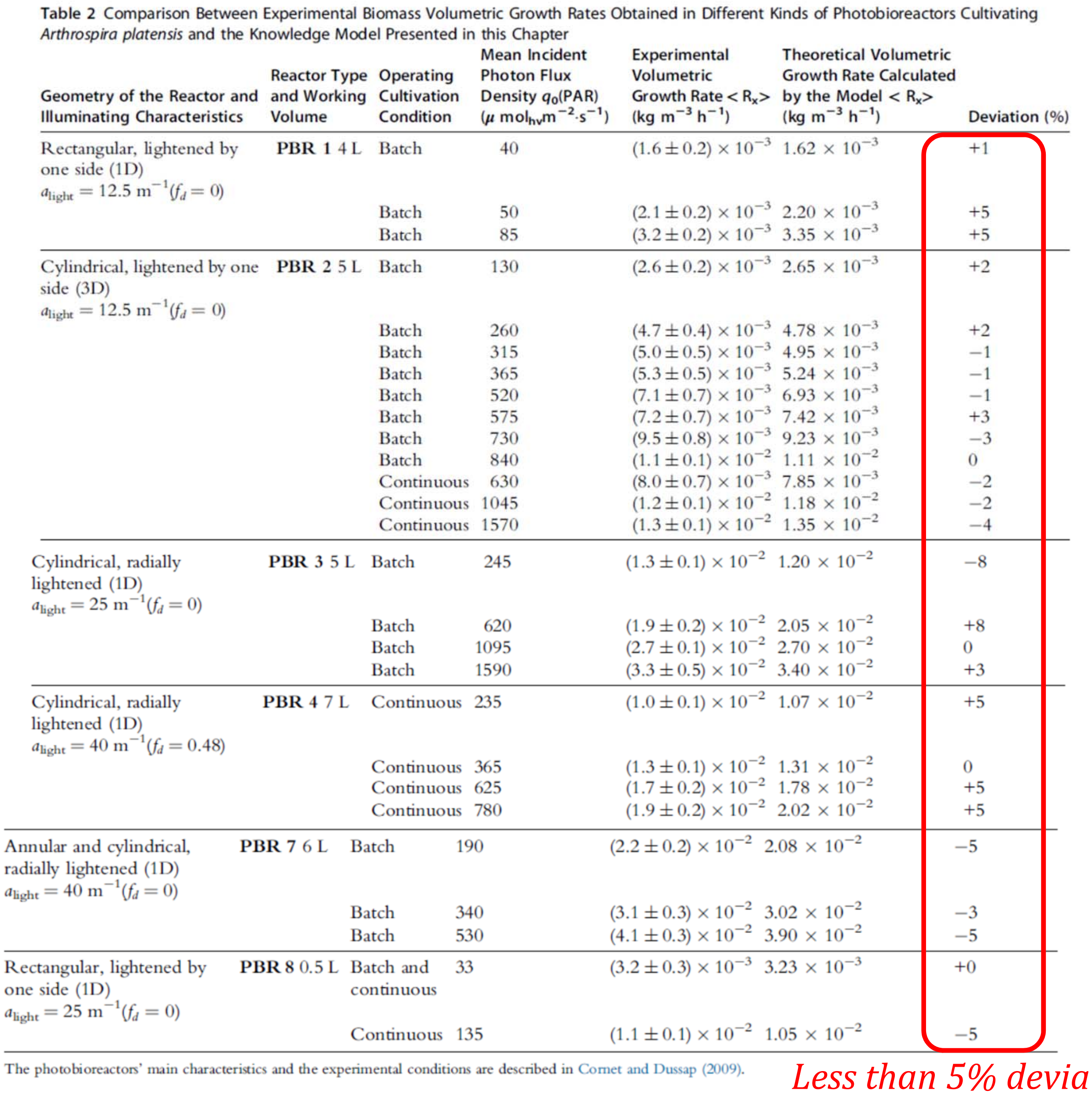


Table 2 Comparison Between Experimental Biomass Volumetric Growth Rates Obtained in Different Kinds of Photobioreactors Cultivating *Arthrospira platensis* and the Knowledge Model Presented in this Chapter

Geometry of the Reactor and Illuminating Characteristics	Reactor Type and Working Volume	Operating Cultivation Condition	Mean Incident Photon Flux Density q_0(PAR) (μ $mol_{h\nu}m^{-2}\cdot s^{-1}$)	Experimental Volumetric Growth Rate $< R_x >$ ($kg\ m^{-3}\ h^{-1}$)	Theoretical Volumetric Growth Rate Calculated by the Model $< R_x >$ ($kg\ m^{-3}\ h^{-1}$)	Deviation (%)
Rectangular, lightened by one side (1D) $a_{light} = 12.5\ m^{-1} (f_d = 0)$	**PBR 1** 4 L	Batch	40	$(1.6 \pm 0.2) \times 10^{-3}$	1.62×10^{-3}	+1
		Batch	50	$(2.1 \pm 0.2) \times 10^{-3}$	2.20×10^{-3}	+5
		Batch	85	$(3.2 \pm 0.2) \times 10^{-3}$	3.35×10^{-3}	+5
Cylindrical, lightened by one side (3D) $a_{light} = 12.5\ m^{-1} (f_d = 0)$	**PBR 2** 5 L	Batch	130	$(2.6 \pm 0.2) \times 10^{-3}$	2.65×10^{-3}	+2
		Batch	260	$(4.7 \pm 0.4) \times 10^{-3}$	4.78×10^{-3}	+2
		Batch	315	$(5.0 \pm 0.5) \times 10^{-3}$	4.95×10^{-3}	−1
		Batch	365	$(5.3 \pm 0.5) \times 10^{-3}$	5.24×10^{-3}	−1
		Batch	520	$(7.1 \pm 0.7) \times 10^{-3}$	6.93×10^{-3}	−1
		Batch	575	$(7.2 \pm 0.7) \times 10^{-3}$	7.42×10^{-3}	+3
		Batch	730	$(9.5 \pm 0.8) \times 10^{-3}$	9.23×10^{-3}	−3
		Batch	840	$(1.1 \pm 0.1) \times 10^{-2}$	1.11×10^{-2}	0
		Continuous	630	$(8.0 \pm 0.7) \times 10^{-3}$	7.85×10^{-3}	−2
		Continuous	1045	$(1.2 \pm 0.1) \times 10^{-2}$	1.18×10^{-2}	−2
		Continuous	1570	$(1.3 \pm 0.1) \times 10^{-2}$	1.35×10^{-2}	−4
Cylindrical, radially lightened (1D) $a_{light} = 25\ m^{-1} (f_d = 0)$	**PBR 3** 5 L	Batch	245	$(1.3 \pm 0.1) \times 10^{-2}$	1.20×10^{-2}	−8
		Batch	620	$(1.9 \pm 0.2) \times 10^{-2}$	2.05×10^{-2}	+8
		Batch	1095	$(2.7 \pm 0.1) \times 10^{-2}$	2.70×10^{-2}	0
		Batch	1590	$(3.3 \pm 0.5) \times 10^{-2}$	3.40×10^{-2}	+3
Cylindrical, radially lightened (1D) $a_{light} = 40\ m^{-1} (f_d = 0.48)$	**PBR 4** 7 L	Continuous	235	$(1.0 \pm 0.1) \times 10^{-2}$	1.07×10^{-2}	+5
		Continuous	365	$(1.3 \pm 0.1) \times 10^{-2}$	1.31×10^{-2}	0
		Continuous	625	$(1.7 \pm 0.2) \times 10^{-2}$	1.78×10^{-2}	+5
		Continuous	780	$(1.9 \pm 0.2) \times 10^{-2}$	2.02×10^{-2}	+5
Annular and cylindrical, radially lightened (1D) $a_{light} = 40\ m^{-1} (f_d = 0)$	**PBR 7** 6 L	Batch	190	$(2.2 \pm 0.2) \times 10^{-2}$	2.08×10^{-2}	−5
		Batch	340	$(3.1 \pm 0.3) \times 10^{-2}$	3.02×10^{-2}	−3
		Batch	530	$(4.1 \pm 0.3) \times 10^{-2}$	3.90×10^{-2}	−5
Rectangular, lightened by one side (1D) $a_{light} = 25\ m^{-1} (f_d = 0)$	**PBR 8** 0.5 L	Batch and continuous	33	$(3.2 \pm 0.3) \times 10^{-3}$	3.23×10^{-3}	+0
		Continuous	135	$(1.1 \pm 0.1) \times 10^{-2}$	1.05×10^{-2}	−5

The photobioreactors' main characteristics and the experimental conditions are described in Cornet and Dussap (2009).

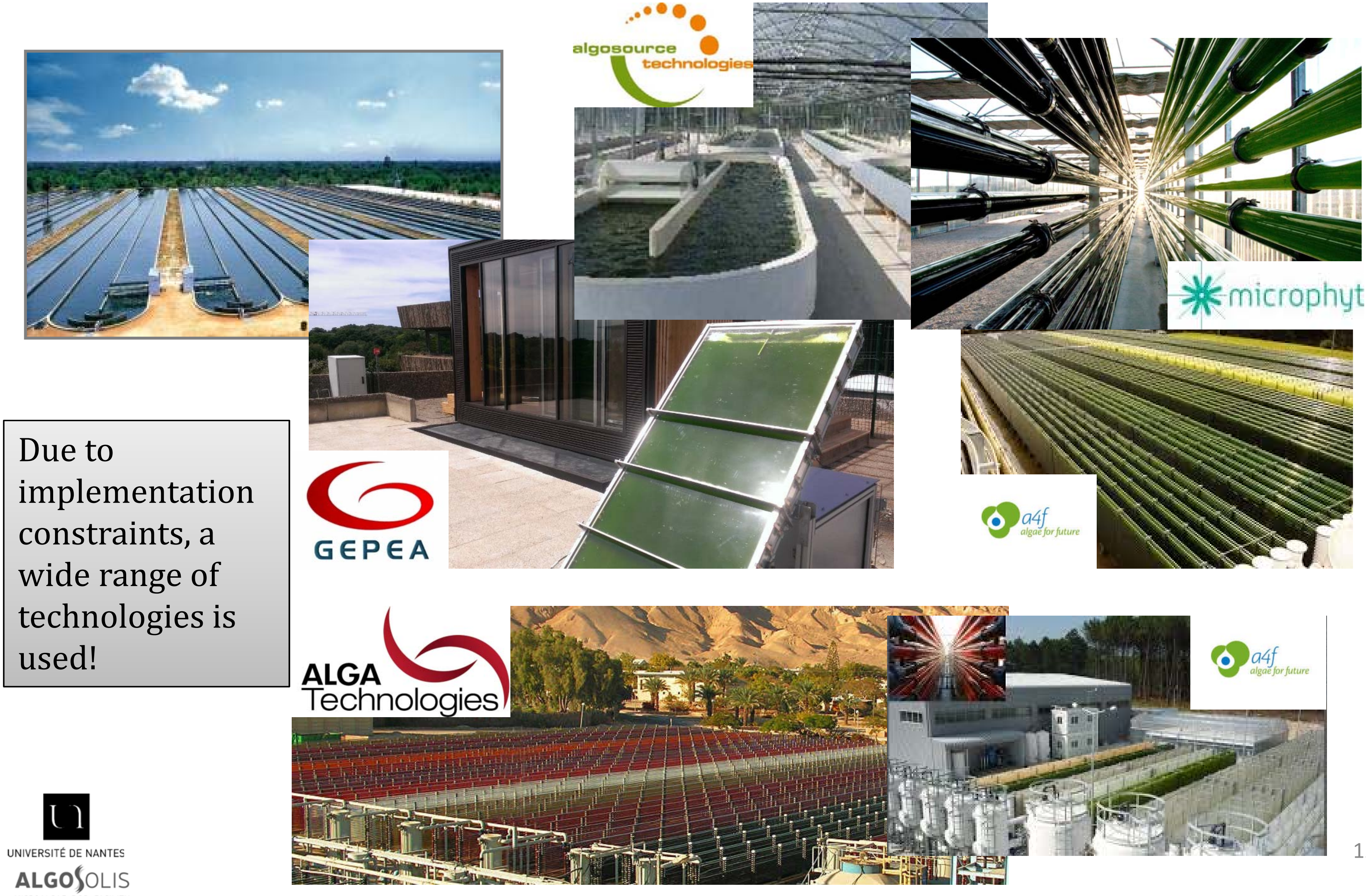
Less than 5% deviation

In summary, robust engineering rules are actually available for (any) PBR scaling

Application to solar (terrestrial) culture

Engineering formulae for the design of solar culture systems

Solar outdoor culture



Due to implementation constraints, a wide range of technologies is used!

Development of engineering rules for the solar case

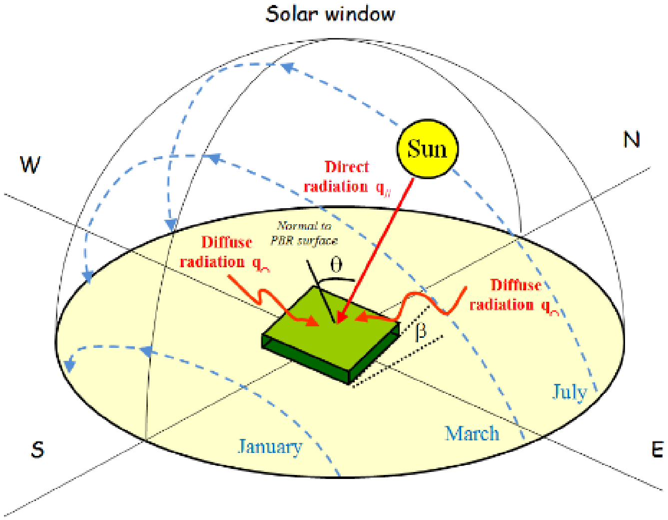
Following engineering formula have been proposed to predict maximal performances:

$$\overline{S_{X\max}} = (1-f_d)\,\rho_{\mathrm{M}} \frac{\overline{\phi'_{O_2}} M_X}{\upsilon_{\mathrm{O}_2-X}} \frac{2\alpha}{1+\alpha} K \ \ln\left[1+\frac{2\,\overline{q}}{K}\right]$$

Maximal surface productivity (g/m²/h)

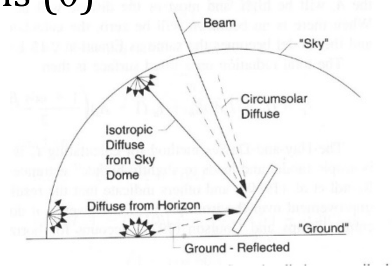
Artificial light (constant light, collimated, normal incidence)

Cornet and Dussap 2009



But sunlight presents time varying :

- Light intensity (PFD, noted q)
- A non negligible contribution of diffuse light (diffuse light fraction, noted x_d)
- and oblique incidence prevails (θ)



Maximal volumetric productivity (g/m³/h)

$$\overline{P_{X\max}} = \overline{S_{X\max}} \frac{S_{\text{light}}}{V_R} = \overline{S_{X\max}} a_{\text{light}}$$

Based on the same approach as developped for artificial light (MELISSA case), the engineering formula was extended to the solar case by taking into consideration all sunlight characteristics:

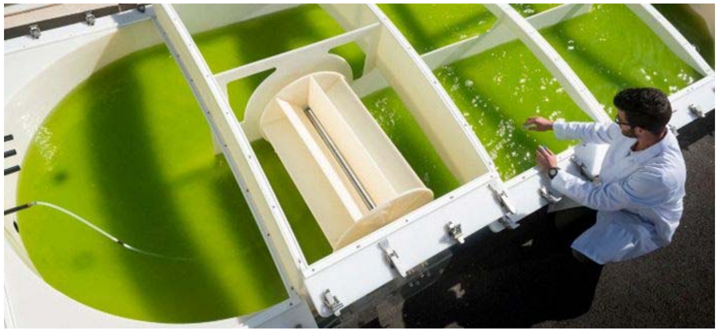
$$\overline{S_{X\max}} = (1-f_d)\,\rho_{\mathrm{M}} \frac{\overline{\phi'_{O_2}} M_X}{\upsilon_{\mathrm{O}_2-X}} \frac{2\alpha}{1+\alpha} \left[\frac{\overline{x}_d K}{2} \ln\left[1+\frac{2\,\overline{q}}{K}\right] + (1-\overline{x}_d)\,\overline{\cos\theta}\, K \ \ln\left[1+\frac{\overline{q}}{K\,\overline{\cos\theta}}\right]\right]$$

Pruvost and Cornet 2012

Example#5 of application: Development of solar photobioreactor technologies


© Jean-Claude MOSCHETTI/AlgoSolis/CNRS Photothèque


Symbio2 project



Tools issued from MELISSA knowledge are nowadays daily used in different projects: mass scale production of microalgae, biological valorisation of CO2 from flue gas, building facade PBR…

Photobioreactor engineering

Application for the development of an intensified technology of solar PBR:
AlgoFilm© technology

Intensification of PBR performances

Areal productivities (kg/m²/day or t/ha/year)

$$\langle S_x \rangle_{max} \propto (1 - fd) ln(1 + \frac{q}{K})$$

Volumetric productivities (kg/m³/day or kg/m³/year)

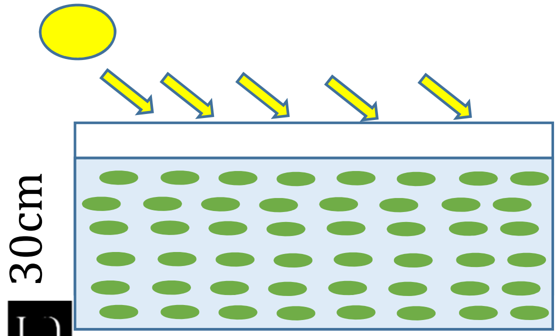
$$\langle P_x \rangle_{max} = \frac{\langle S_x \rangle_{max} \times S_{light}}{V_R} \propto \boldsymbol{a_{light}} \langle S_x \rangle_{max}$$

The specific illuminated surface to volume ratio $\boldsymbol{a_{light}}$

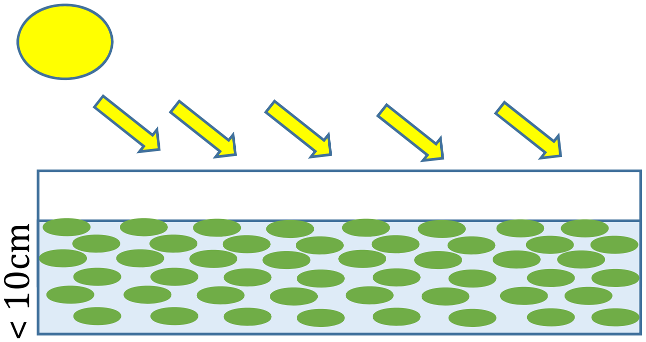
$$a_{light} = \frac{S_{light}}{V_R} = \frac{1}{L}$$

As shown by engineering rules, productivities are governed by few engineering parameters

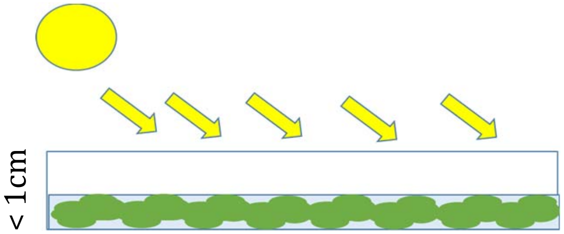
- The design dark fraction (which has to be made **as low as possible:** $f_d \rightarrow 0$)
- **Areal productivities are mainly fixed by light received** (q), and increasing light received will increase kinetics performances
- **Volumetric productivities can be increased while keeping constant areal productivities** (and limits are from the engineering point of view, as determined by the limit in achievable value of a_{light})



Open systems
$Cx_{max} \approx 0{,}2$ (g/l)



Standard PBR
$Cx_{max} \approx 1\text{-}10$ (g/l)

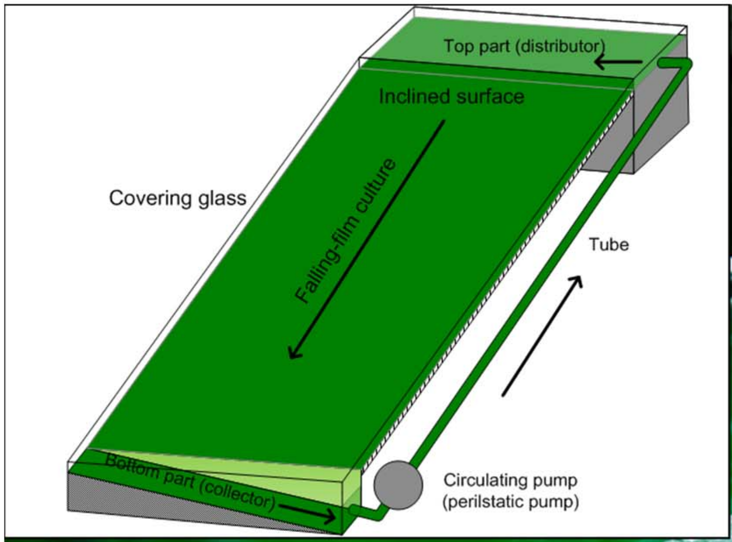


High-Cell density culture
(High Volumetric Productivity PBR)
$Cx_{max} > 10$ (g/l)

Development of a solar intensified technology: AlgoFilm© photobioreactor

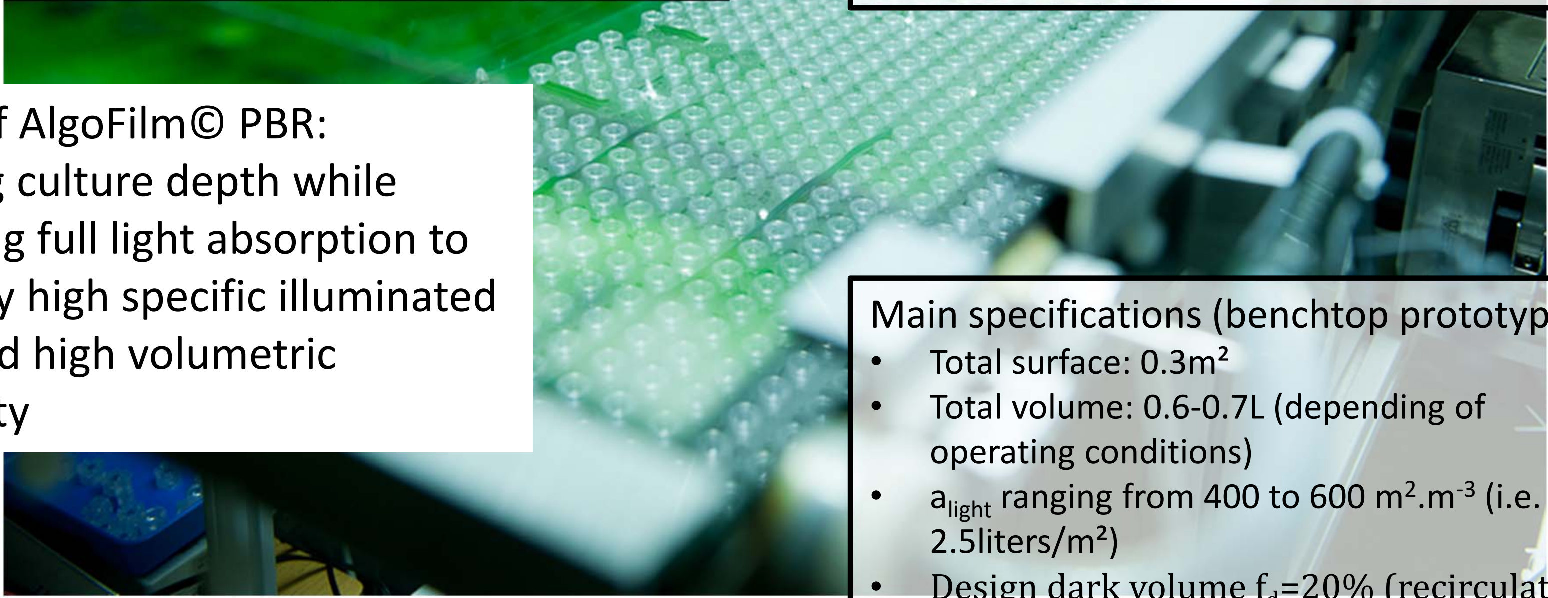
INSTITUT PASCAL

GEPEA
UMR CNRS 6144



Engineering principles

- Based on a falling-film principle, with injection on culture broth on the top of a titled surface
- Covered geometry (glass plate) without contact of the culture on the optical surface
- Loop culture circulation using a peristatic pump (low shear-stress)
- Air+CO2 injection in the culture headspace
- Designed for batch, continuous and semi-continuous culture with full regulation of culture conditions (T, pH)



Concept of AlgoFilm© PBR: decreasing culture depth while maintaining full light absorption to obtain very high specific illuminated surface and high volumetric productivity

Main specifications (benchtop prototype)

- Total surface: $0.3m^2$
- Total volume: 0.6-0.7L (depending of operating conditions)
- a_{light} ranging from 400 to 600 $m^2.m^{-3}$ (i.e. 1.7-2.5liters/m^2)
- Design dark volume f_d=20% (recirculating pump)

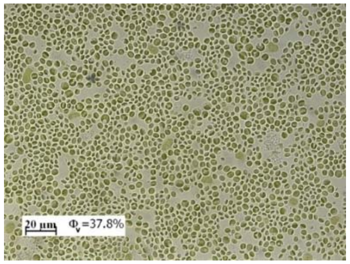
UNIVERSITÉ DE NANTES

ALGOSOLIS
MICROALGAE R&D FACILITY

Experimental validation of AlgoFilm© performances

Pruvost et al. 2017

Cultivation of *C. vulgaris*



- Growth medium (Sueoka, 1960) adjusted for high biomass concentration

NH_4Cl and $NaHCO_3$ replaced by NH_4HCO_3 to avoid from Na^+ and Cl^- accumulation (salt crystals formation)

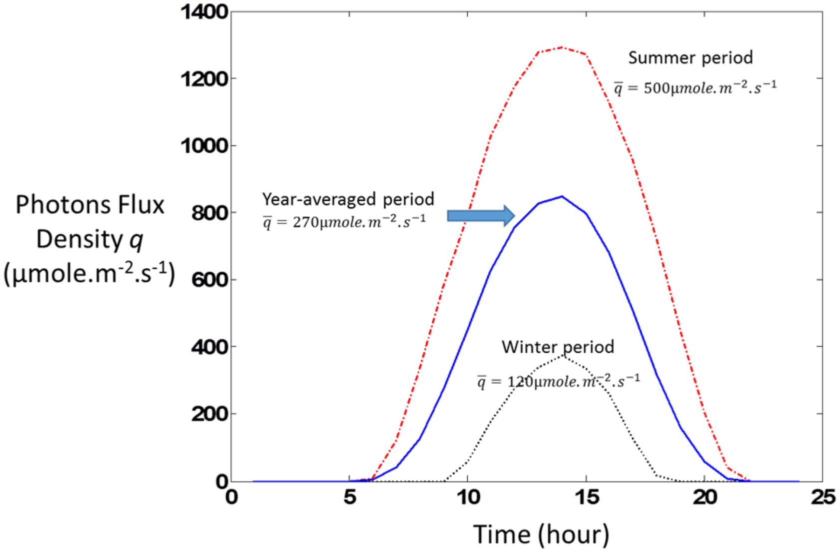
Adjustment of main nutrient concentrations to avoid from mineral limitation

ion	% assimilated during the biomass growth (Mean±SD)
PO_4^{2-}	4.74 ± 0.3
SO_4^{2-}	2.73 ± 0.1
NH_4^+	16.53 ± 0.2
K^+	1.79 ± 0.2
Mg^{2+}	0.54 ± 0.01
Ca^{2+}	0.08 ± 0.01

- pH regulation at 7.5 (automatic CO_2 injection)
- Temperature regulation at 25 °C (automatic air draft on the rear side)

Evaluation under simulated day-night cycles and with constant light (LED panel)

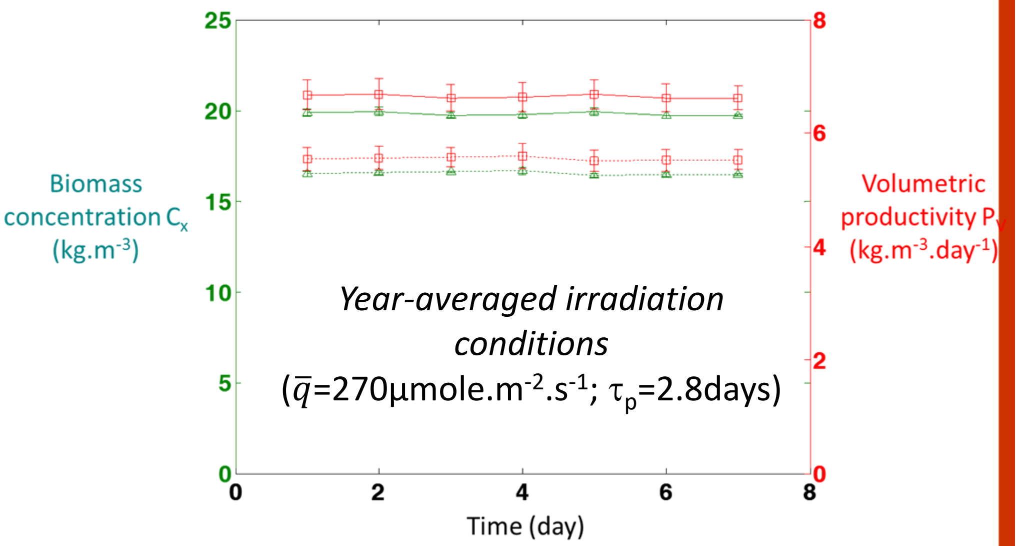
- ✓ Reproducible illumination conditions
- ✓ Application of 3 typical irradiation conditions of Nantes location (winter, summer, year averaged)



Experimental validation of AlgoFilm© performance

Characterization in semi-continuous mode (1 harvest at 17h each day)

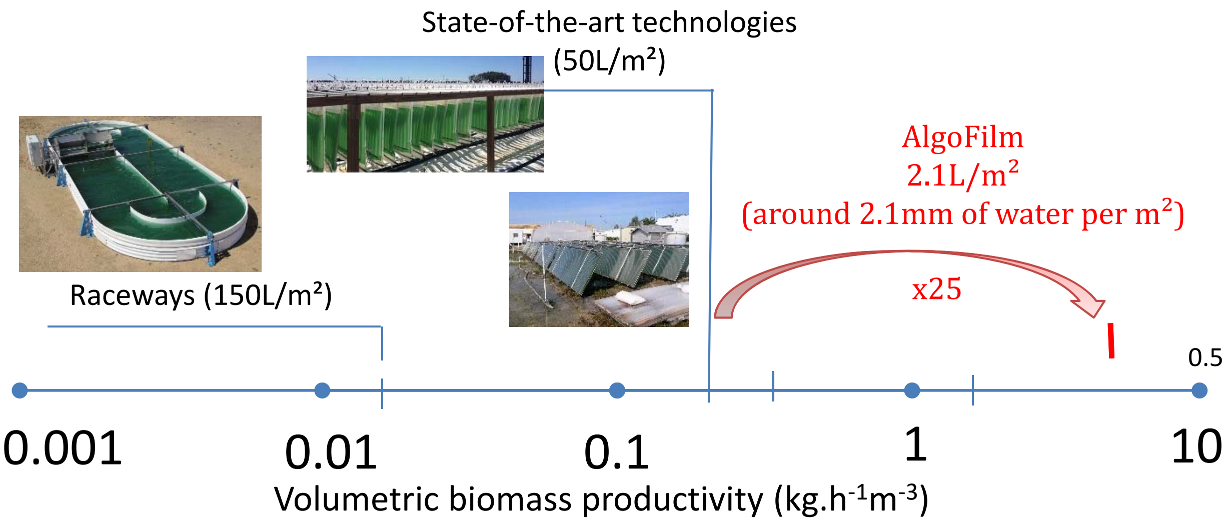
- **Steady-state were maintained without deviation** (23 days for winter irradiation conditions)
- Performances typical of light-limited culture: productivity increase with the PFD
- Biomass concentrations > 10kg.m^{-3} corresponding to volumetric productivities > 3 kg.m^{-3}.day^{-1} in all cases
- Maximal productivity: **5.7 kg.m^{-3}.day^{-1}** in day-night cycles with year-averaged conditions (C_x =17kg.m^{-3}) (x100 when compared to state-of-the-art technologies)



AlgoFilm experimental productivity was found very close to the one expected from the prior theoretical design (10% deviation).

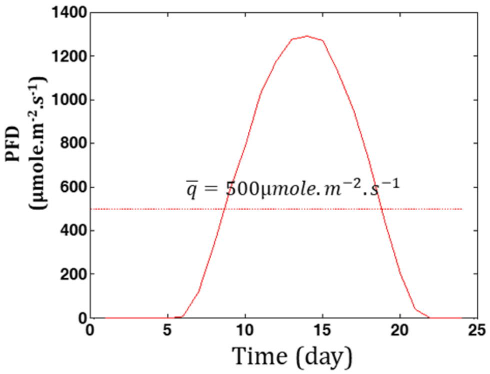
MELISSA project gave a corpus of the setting of a highly robust and reliable approach!

Experimental validation of AlgoFilm© performance



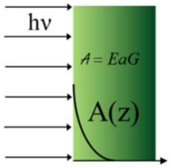
By using knowledge issued from spatial research, a breakthrough technology was designed for solar production

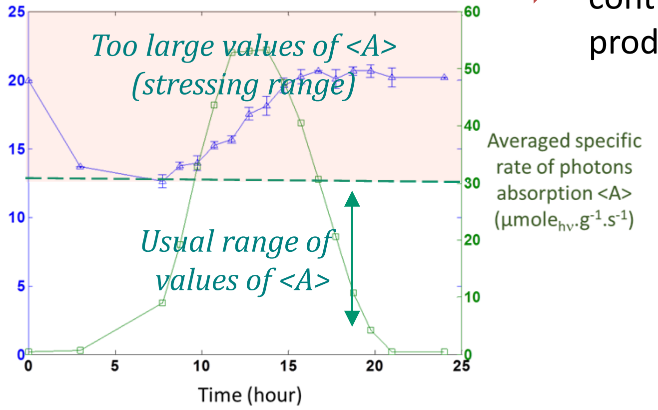
Note for biofuel application: due to water need reduction, a positive energy balance can be expected (EROI: 2.5-3.4)



But solar operation of intensified technologies is challenging
→ dynamic process with high light absorption rates

Current effort is for the development of advanced control strategies for a robust and optimized production (still based on Melissa models…)





Ex : Optimization of biomass production (Crit 1) while keeping low risk of biological drift due to too large rates of photons absorption (Crit 2)

$$Crit1 = \max_{D(t)} \int_0^T D(t)X(t)dt$$

$Crit2$: $A < 30\ \mu mol_{hn}.g^{-1}.s^{-1}$

Conclusion

- The long-term research on Compartment IV from MELISSA LSS leads nowadays to a robust corpus of advanced mathematical models for microalgal culture
- Engineering tools have been proposed to predict with a high accuracy the effect of engineering and operational parameters on PBR performances.
- They are used by GEPEA and coll. for terrestrial developments in the emerging field of industrial exploitation of microalgae for human needs

  → Prediction of biomass production as a function of PBR geometry, location, sunlight received…

  → Guidelines for PBR performances intensification were set, leading to the rational design of AlgoFilm©-PBR.

- The effort will be pursued in the future for the optimisation of solar production (advanced control based on knowledge modeling) and for the development of microalgal industry (mass scale culture, CO2 valorisation…)

Some cuttings from Compartment IV…

Books

Photobioreaction Engineering, Special Issue of Advances Chemical Engineering (Edited by J.Legrand, Elsevier, 2016)
Algae Biotechnology: Products and Processes (Edited by Bux and Chisti, Springer, 2016)
Pruvost et al. Large scale production of algal biomass: Photobioreactors
Microalgal Biotechnology (Edited by Posten, De Gruyter, 2012)
Pruvost et al. Knowledge models for engineering and optimization of photobioreactors

Scientific papers

- Cornet, J.F., Dussap, C.G., Cluzel, P., Dubertret, G. 1992. A structured model for simulation of cultures of the cyanobacterium Spirulina platensis in photobioreactors. 1. Coupling between light transfer and growth kinetics. Biotechnology and Bioengineering, 40(7), 817-825.
- Cornet, J.F., Dussap, C.G., Gros, J.B. 1994. Conversion of radiant light energy in photobioreactors. *AIChE Journal*, **40**(6), 1055-1066.
- Cornet, J.-F. 2010. Calculation of optimal design and ideal productivities of volumetrically lightened photobioreactors using the constructal approach. Chemical Engineering Science, 65(2), 985-998
- L.POTTIER, J.PRUVOST, J.DEREMETZ, J.F.CORNET, J.LEGRAND, C.G.DUSSAP, A fully predictive model for one-dimensional light attenuation by Chlamydomonas reinhardtii in a torus reactor, Biotechnology and Bioengineering 91, n°5, 569-582, 2005.
- Cornet, J.F., Dussap, C.G. 2009. A simple and reliable formula for assessment of maximum volumetric productivities in photobioreactors. Biotechnology Progress, 25, 424-435.
- H.TAKACHE, J.F.CORNET, J.PRUVOST, Kinetic modeling of the photosynthetic growth of Chlamydomonas reinhardtii in a photobioreactor, Biotechnology progress, 28(3), 681-92, 2012.
- Dauchet, J., Blanco, S., Cornet, J.F., El Hafi, M., Eymet, V., Fournier, R. 2013. The practice of recent radiative transfer Monte Carlo advances and its contribution to the field of microorganisms cultivation in photobioreactors. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **128**, 52-59.
- PRUVOST J., CORNET J.F., LE BORGNE F., GOETZ V., LEGRAND L., Theoretical investigation of microalgae culture in the light changing conditions of solar photobioreactor production and comparison with cyanobacteria, Algal Research, 10, 87-99, 2015.
- PRUVOST. J., LE GOUIC B., LEPINE O., LEGRAND J., LE BORGNE F., Microalgae culture in building-integrated photobioreactors: biomass production modelling and energetic analysis, Chemical Engineering Journal, 284, 850-861, 2016.
- A.SOULIES, C.CASTELAIN, T.BURGELEA, J.LEGRAND, J.F.CORNET, H.MAREC, J. PRUVOST, Investigation and modeling of the effects of light spectrum and incident angle on the growth of chlorella vulgaris in photobioreactors, Biotechnology progress, 2016.
- Pruvost, J., Le Borgne, F., Artu, A., Legrand, J. 2017. Development and characterization of a thin-film solar photobioreactor (AlgoFilm©) based on process ensification principles. Algal Research(21), 120-137.

UNIVERSITÉ DE NANTES

INSTITUT PASCAL

GEPEA

CONTACT
Jeremy PRUVOST
algosolis@univ-nantes.fr
www.algosolis.com

Thank you for your attention